Testing Parameterizations of Submesoscale Ocean Variability: Resolutions and Power Spectra

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Award Number: N00014-05-1-0492

LONG-TERM GOALS

To develop a framework for evaluating the performance of subgrid scale parameterizations in ocean models with explicitly resolved mesoscales and to apply this framework to Monterey Bay simulations.

OBJECTIVES

To design a system for testing submesoscale parameterization of the ocean models with realistic littoral settings; to apply the framework to the conditions of Monterey Bay and to perform the simulations of the AESOP field experiment period, when extensive observations are available; to summarize the results of model-model and model-data comparisons in the form of conclusions and recommendations with regards to the fidelity of various submesoscale parameterizations, their optimal settings, and their effectiveness in terms of their impacts on the resolved-scale ocean variability; to estimate spectral distributions of ocean variability and energy transfer between different scales; compare results with other (theoretical and observational) estimates; investigate the scalability of submesoscale parameterizations, and the role which these parameterizations play in setting up the spectral properties of the solution.

APPROACH

This project develops and applies a framework for evaluating the performance of subgrid scale parameterizations in ocean models where the mesoscale is explicitly resolved. A nesting system of models using the Regional Ocean Modeling System (ROMS; Song and Haidvogel 1994; Shchepetkin and McWilliams 2005; Curchitser et al. 2005) with resolutions varying from 40 km to 300 m is planned for modeling ocean variability in Monterey Bay and the surrounding regions of Pacific Ocean. The separation of impacts of model resolution on the mean model dynamics and on the parameterization of subgrid scale variability is implemented via a system of spatial pre-filtering for model fields entering the parameterization schemes. Such a pre-filtering system makes it possible to change (reduce) the effective resolution of inputs to a subgrid parameterization scheme, while keeping the resolution of the prognostic dynamical scheme unchanged. This approach allows us to assess the effect of the resolution-dependent sub-gridscale parameterization on the mean flow. Furthermore, it allows a direct comparison between parameterization schemes used with the models of different resolutions. Results obtained from comparisons between models and parameterizations of various resolutions will be ground-truthed via the comparison with the data collected during the AESOP field experiment in Monterey Bay. Spectral wavenumber distributions of ocean variability and energy transfer between different scales will be computed and analyzed, as a way to evaluate the fidelity of model simulations, to investigate the scalability of small-scale variability in the ocean models, observations, and parameterizations, and to infer the desirable features of the parameterization schemes.

WORK COMPLETED

We finished the setup of the circulation mode for the Monterey Bay runs which we are performing now (MBR run). This included grid generation, preparation of forcing, boundary and initial condition files, necessary numerical upgrades, and trial runs. One of the main sub-gridscale parameterizations we plan to explore is the vertical mixing scheme KPP (Large et al. 1994; Large and Gent 1999). There have been several recent upgrades to this scheme which to date have not been incorporated into our circulation model, ROMS. We have upgraded the KPP scheme in the ROMS code for the needs of this project.

In a continued effort to analyze the suite of high-, medium-, and low-resolution model simulations, we have performed a new “low resolution” run for the Pacific Ocean using the ROMS model. This new run (hereafter called “NPac2”) has a spatial resolution of 0.18^o, upgraded from 0.4^o for our first low-resolution run (previously called “NPac”, Curchitser et al. 2005). The model uses 42 terrain-following vertical levels. The model domain extends from 30^{o}S to 65^{o}N, and from 90^{o}E to 290^{o}E. The surface forcing is derived from the CORE data set (Large and Yeager, 2004). The high-resolution North Pacific model grid is nested within a 1^o global ocean hindcast simulation using the National Center for Atmospheric Research (NCAR) Community Climate System Model (CCSM). The initial conditions were derived from a fully evolved ocean model so that a relatively short period of adjustment is needed. The NPac2 simulation bridges a gap in our hierarchy of model simulations with different spatial resolutions.

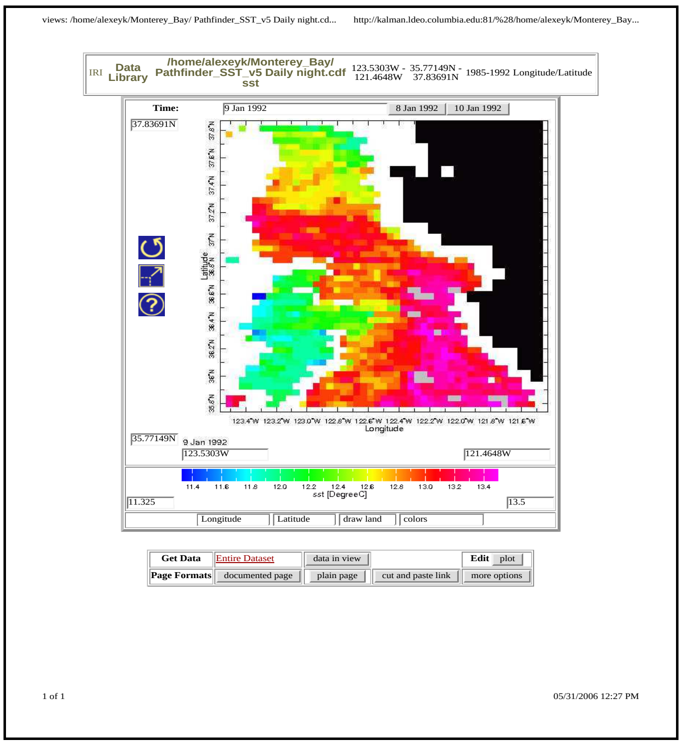
While new high-resolution ROMS MBR simulations are being performed, we worked on the systematic evaluation of already available ROMS simulations for the Monterey Bay area. We used two simulations, with resolutions of roughly 0.18^o degree and 3 km, which were produced for the entire North Pacific domain (NPac2, see above) and for California Coastal Currents system (CCS; Powell et al. 2006) respectively. The results of these simulations were compared with available satellite data: AVISO altimetry analysis for sea surface heights (SSH) and Pathfinder V5.0 AVHRR data set for sea surface temperatures (SST). The analysis of the Npac2 run and its comparison with the altimetry data provided a very interesting example of the effect of changing model resolution. With a better representation for the mesoscale eddies, the NPac2 run produced multiple mid-ocean zonal jets in the zonal velocity field, consistent with recent studies using eddy-resolving model simulations of global oceans (Richards et al. 2006) and satellite observations (Maximenko et al. 2005). Comparison of the CCS run with nighttime and daytime SST data in Monterey Bay and surrounding areas identified systematic differences in means and standard deviations of daily SST values. The effect of increasing resolution on these differences will be a subject of further research.

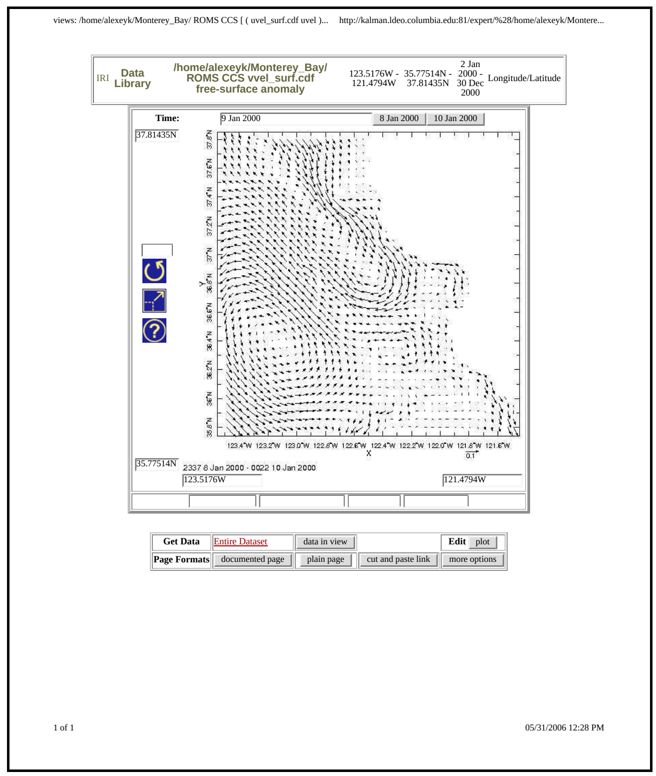
Selected data sets for Monterey Bay and surrounding areas, including Pathfinder SST data for the period 1985-2006 and the ROMS CCS simulations for year 2000, were made directly accessible at

A web site for obs & model data for Monterey Bay

(http://kalman.ldeo.columbia.edu:81/%28/home/alexeyk/Monterey_Bay/%29readfile/)

Model data (CCS run)





Observation (Pathfinder SST)

***Figure 1.** Visualization examples for Pathfinder SST and CCS surface velocity vectors via our Ingrid-based Data Catalog providing the access to selected Monterey Bay area data at http://rainbow.ldeo.columbia.edu/∼alexeyk/Monterey Bay.html*

http://rainbow.ldeo.columbia.edu/∼alexeyk/Monterey_Bay.html
The access is via the Ingrid-based Data Catalog, a tool popular among climatologists for its ease of data manipulation, visualization, and download in a variety of formats. Some visualization examples are given in Figure 1. MODIS SST and chlorophyll-a data, extracts from the globally complete 5km OSTIA analysis of SST from the U.K. MetOffice, and a binned representation of historical in situ data for Monterey Bay are planned to be added in near future.

RESULTS

We performed a comparison of the SST simulated by the ROMS CCS model run with that from the 4 km AVHRR Pathfinder, Version 5.0, accessed via the NODC ftp://data.nodc.noaa.gov/pub/data.nodc/pathfinder/. There are two Pathfinder products, daytime and nighttime SST. Figure 2 presents means and standard deviations of the model run for its entire period, spanning one year of 2000, along with the same statistics for the two Pathfinder SST products, for a 20 year period 1985-2004. Because of major data gaps in Pathfinder data sets for this area, averages for a single year (e.g. 2000) produce noisy patterns, roughly consistent with 20 year averages shown in Figure 2. Both Pathfinder products show strong off-coast SST gradient, while the model simulation produces the SST which is much more uniform and generally warmer than Pathfinder products. Model also produced an increase in temporal SST variability towards the coast, a feature not confirmed by Pathfinder observations.

Daytime SSTs are warmer than nighttime values, with the average difference increasing from about 0.2^{o}C in the open ocean to 0.6-0.8^{o}C near the coast. The temporal variability around these values is about 0.5-0.6^{o}C in standard deviation and has a pronounced minimum inside Monterey Bay (Figure 3). Because of the mean warm bias in the model SST, its mean state is naturally closer to the daytime SST than nighttime SST (Figure 4), but the standard deviation of the former difference is slightly smaller too. Despite these differences, due to the general strength of the annual cycle, the simulated and observed SST are significantly correlated at all off-coast locations (Figure 5).

A detailed study of the SST simulation in the 300m MBR run, currently under way, will make it possible to find out the causes of and, possibly, to correct the SST bias in the model. Visual inspection of sample SSH fields from the new run (Figure 6) confirms the presence of small-scale dynamical features in this simulation.

Our newly produced Npac2 run provides a very interesting example of the effect of the increased model resolution. With a better representation for the mesoscale eddies, the NPac2 run produces multiple mid-ocean zonal jets in its zonal velocity fields. This is consistent with recent studies based on eddy-resolving model simulations of global oceans (Richards et al. 2006) and satellite observations (Maximenko et al. 2005). Figure 7 shows a 100 week average of zonal geostrophic velocity derived from AVISO satellite altimetry (Ducet et al., 2000), while Figure 8 displays a one year average of surface zonal velocity from the NPac2 run. Both fields are presented as anomalies with respect to their long-term mean, annual and semiannual variations. The ocean model also provides information for the deep ocean. Figure 9 presents a one year averaged zonal velocity field at 1000m from the NPac2 run. The signature of mid-ocean zonal jets is enhanced in the deep ocean, most likely because it is far removed from the direct influence of the atmospheric noise at the surface.

The emergence in the NPac2 run of zonal jet structures, which were not robustly present in the earlier NPac run of lower resolution by Curchitser et al. (2005), is an example that new phenomena can emerge

Statistics of daily values on 4km spatial grid of ROMS CCS simulation and Pathfinder , ^{o}C

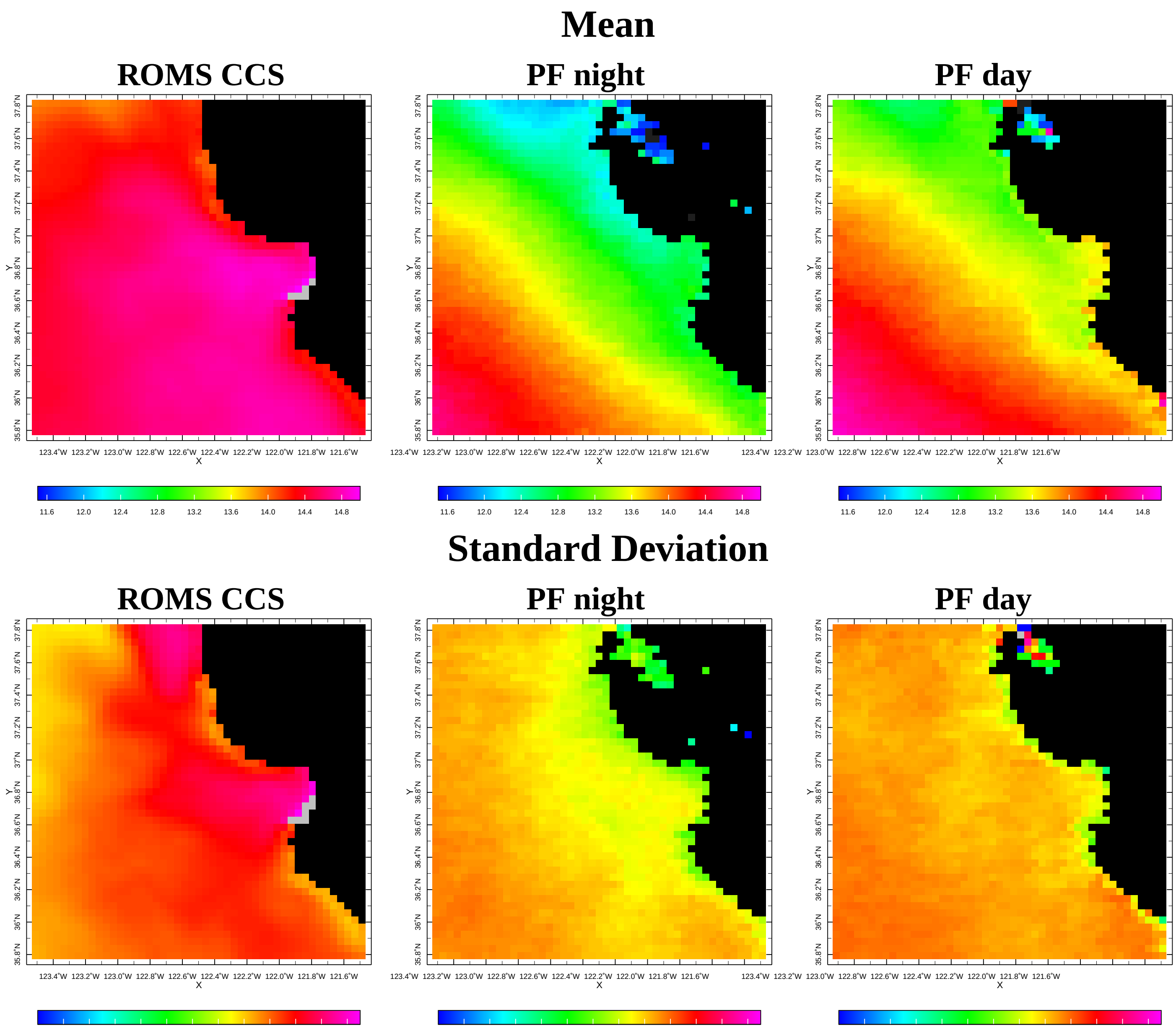


Figure 2. Means and standard deviations of SST values on 4km spatial grid for ROMS CCS simulation (year 2000) and Pathfinder, Version 5.0 (1985-2004 period). Units are °C.

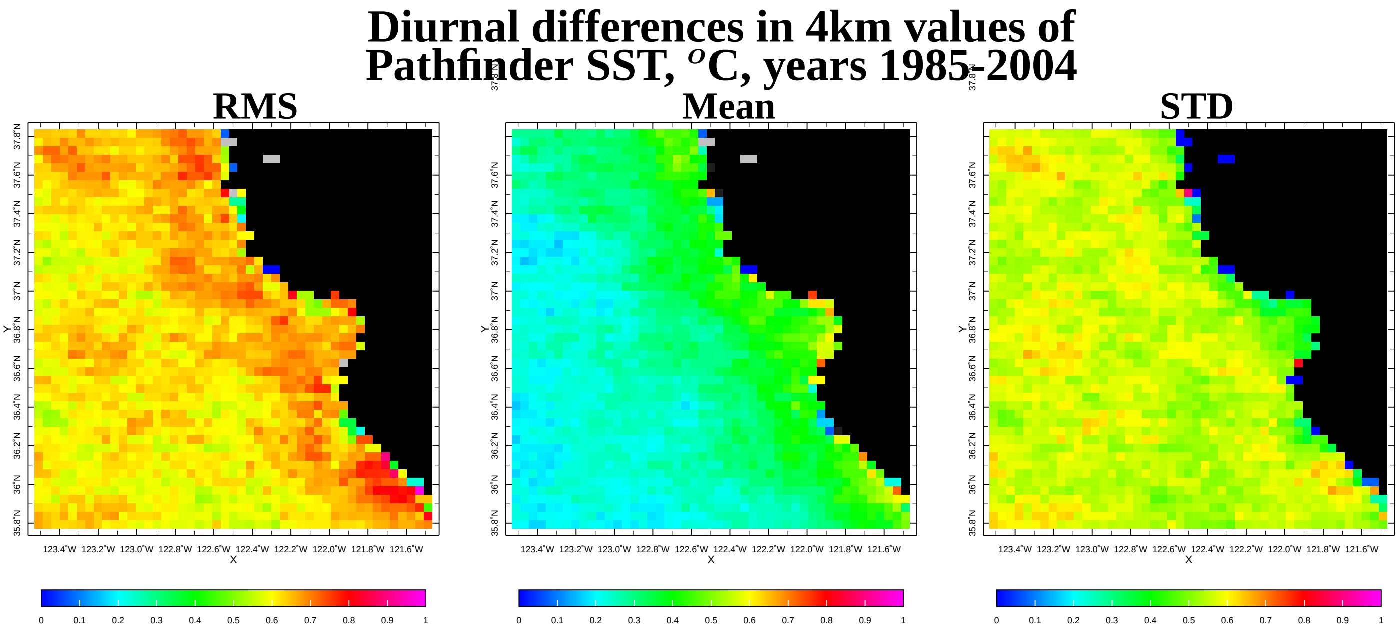


Figure 3. Diurnal differences in 4km values of Pathfinder SST, ^{o}C. Left panels show RMS difference, central and right panels subdivide it into the mean difference and standard deviations. Calculations performed for daily values for the 20 year period 1985-2004.

as the model resolution increases. In this case, the inclusion of a more complete spectrum of mesoscale eddies apparently enables an up-scale energy cascade into zonal jets. When mesoscale eddies are poorly resolved, as was the case for the NPac run, zonal jets, which represent larger scale structures, are missing as well. Therefore the interaction between scales affects not only the amplitude and variance of the large-scale flow, but also its fundamental qualitative character. This principle may apply to the interaction between mesoscale and submesoscale variability too.

The similarity between zonally elongated structures in the satellite observations (Figure 7) and our NPac2 run (Figure 8) can be rigorously quantified (Huang et al. 2006). Figure 10 shows the quantity α, named the "degree of anisotropy" and defined such that $\alpha = 0$, 1, and -1 correspond to an isotropic, purely zonal, and purely meridional flow. The anomalous surface velocity field (u, v) from the model simulation and geostrophic velocity (u_g, v_g) for satellite observations, both records being about 12-year long, are used to compute α for the North Pacific between 12^{o}N and 60^{o}N as a function of time averaging. The value of α increases with time averaging, showing a good agreement between satellite (black) and model (red) data. For weekly values, the satellite-derived surface velocity is nearly isotropic while the model simulation shows a slightly positive zonal anisotropy. When longer-term averaging is applied, both products show significantly positive zonal anisotropy. The agreement is good not only in averages for the entire North Pacific Ocean, but also that for its individual sub-domains, as detailed by Huang et al. (2006). The measure of anisotropy α will be used for testing submesoscale parameterization schemes with our high-resolution ocean simulations for Monterey Bay.

IMPACT/APPLICATIONS

The work which has been performed in this project develops the foundation for fulfilling our program of testing submesoscale parameterizations in Monterey Bay ocean simulations. The theoretical results reported above have important impacts on our testing plans for scheme performances. Our verification study of the SST simulation in 3km model defines the baseline for comparisons of higher resolution

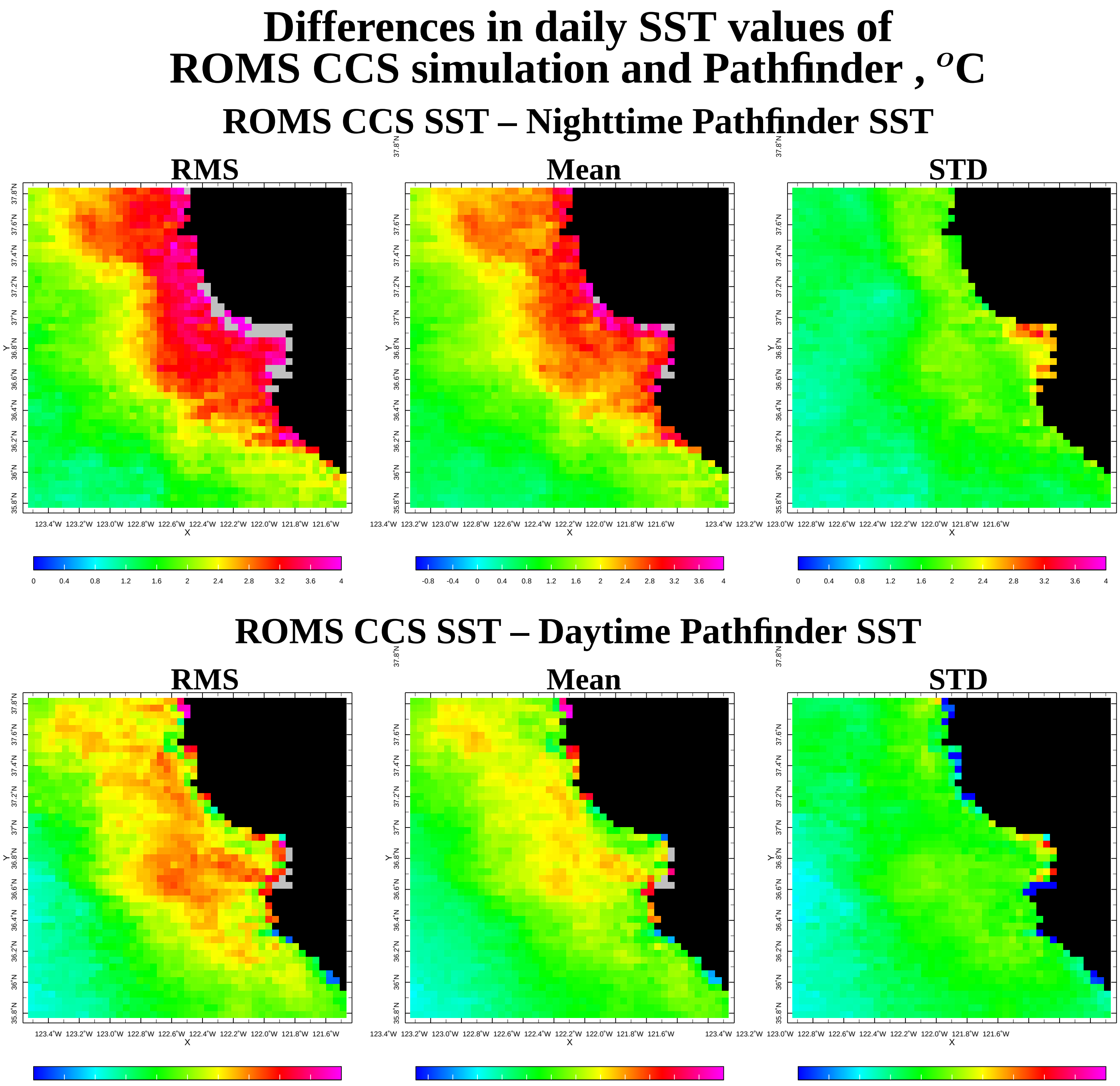


Figure 4. Differences in SST values on 4km spatial grid of ROMS CCS simulation and Pathfinder. Left panels show RMS difference, central and right panels subdivide it into the mean difference and standard deviations. Calculations performed for daily values for the year 2000. Units are ^{o} C.

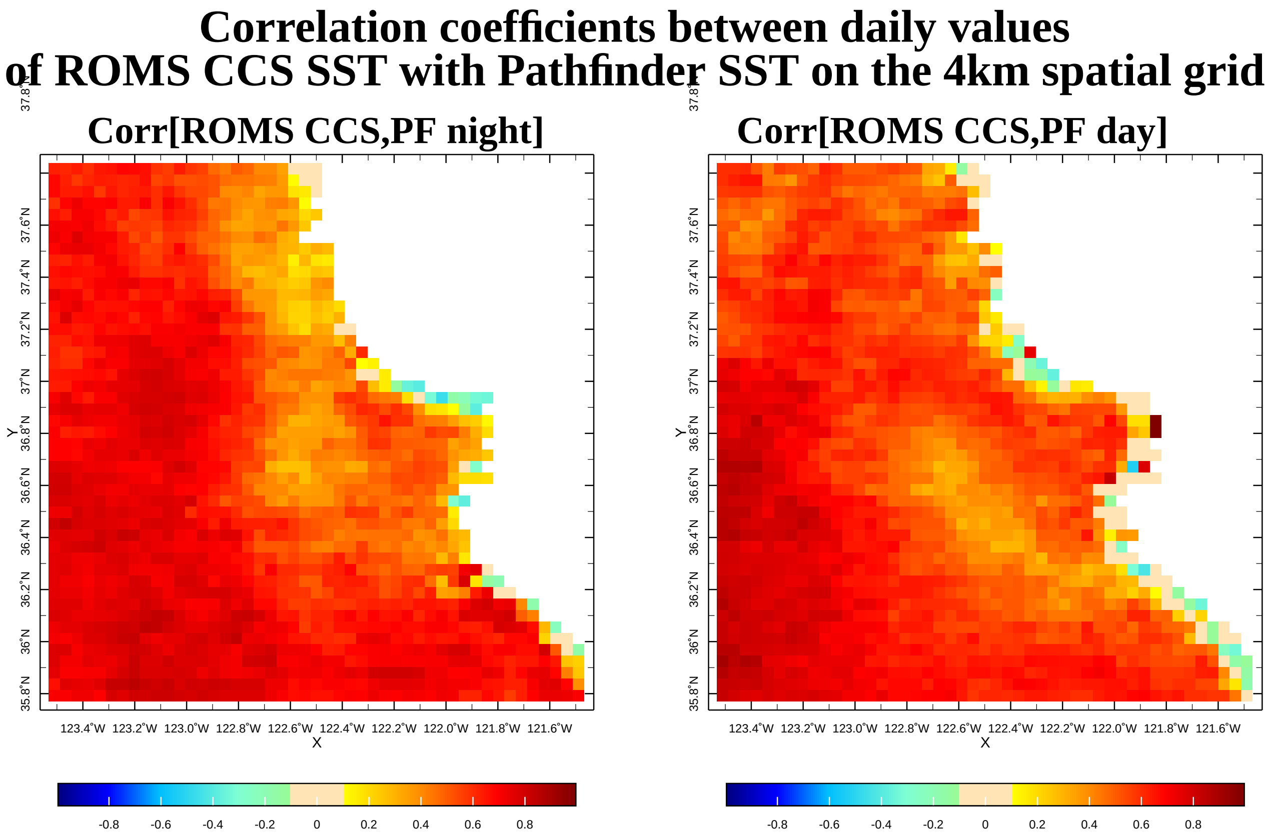


Figure 5. Correlation coefficients between daily values of ROMS CCS SST with Pathfinder SST for (left) nighttime and (right) daytime products, computed for year 2000 on the 4km spatial grid.

simulations. The up-scale energy cascade responsible for zonal jet structures in the NPac2 simulation is expected to be accompanied by the down-scale enstrophy cascade, which, theoretically, can proceed to very small scales, and might be traceable in high-resolution Monterey Bay simulations. A measure of anisotropy α investigated in our recent work using the NPac2 and satellite altimetry data provides a useful criterion for testing submesoscale parameterization schemes.

RELATED PROJECTS

This projects builds on a considerable body of model development and expertise accumulated by other projects that fund ROMS-based research, in particular the GLOBEC consortium (NSF grants OCE00-02892, OCE01-13461, and OCE04-35592), which partially supports E.N.Curchitser. The results of the present project will further improve ROMS simulations and thus will be found useful by other ROMS-supporting projects, including GLOBEC.

Samples of daily sea surface height fields
from the ROMS MBR simulation with 300m spatial resolution

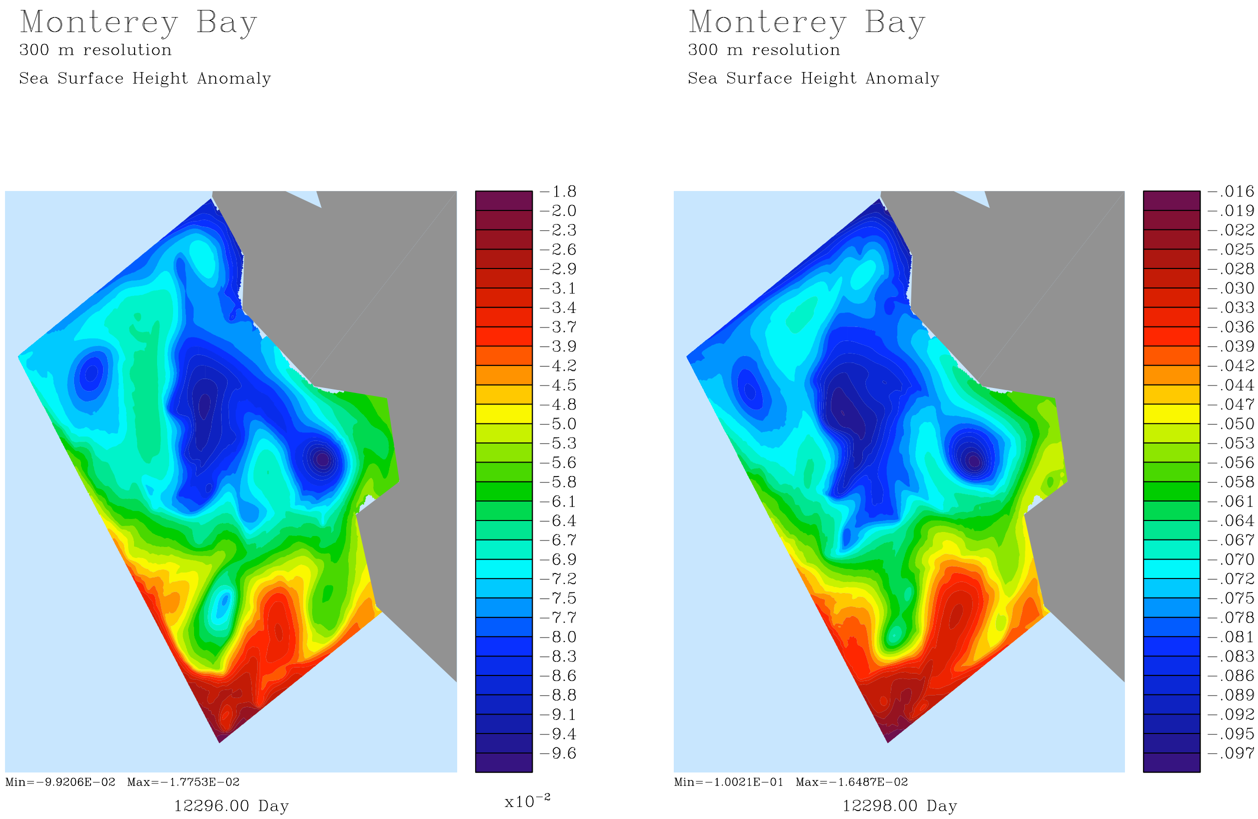


Figure 6. Daily sea surface height fields from the ROMS MBR simulation with 300m spatial resolution.

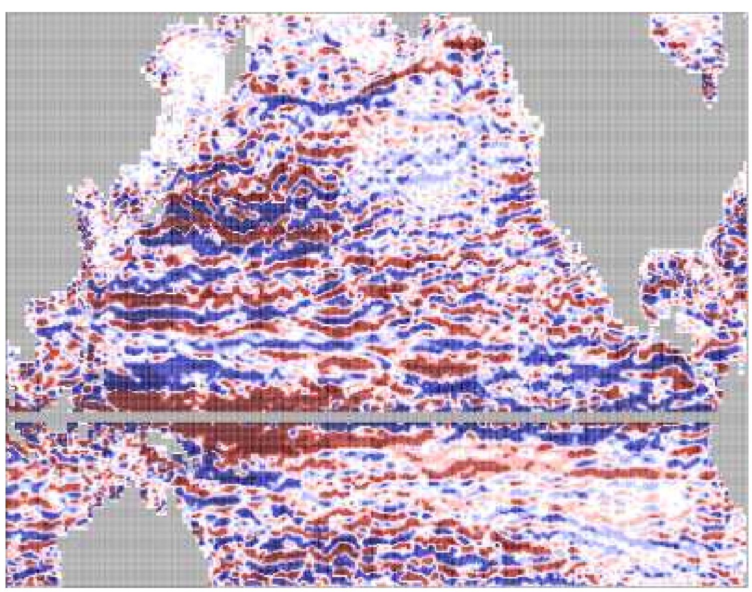


Figure 7. A 100 week average of anomalous surface geostrophic zonal velocity derived from the AVISO altimetry data set. Color levels are ±0.5, 1, 2, 5 cm/s, with red and blue colors used for positive and negative values, respectively.

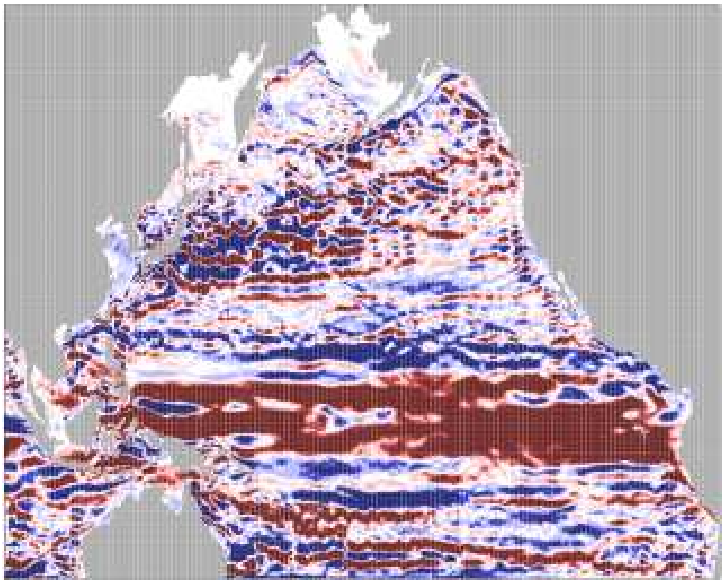


Figure 8. A one year average of anomalous surface zonal velocity from the NPac2 run. Color levels are $\pm$1, 2, 4, 6 cm/s, with red and blue colors used for positive and negative values, respectively.

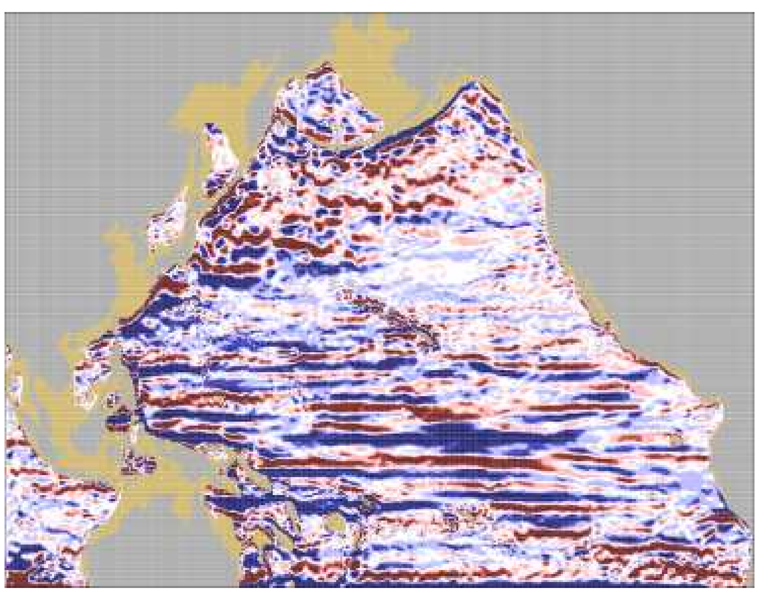


Figure 9. A one year average of zonal velocity at 1000m depth from the NPac2 run. Color levels are $\pm$0.5, 1, 2, 3 cm/s, with red and blue colors used for positive and negative values, respectively.

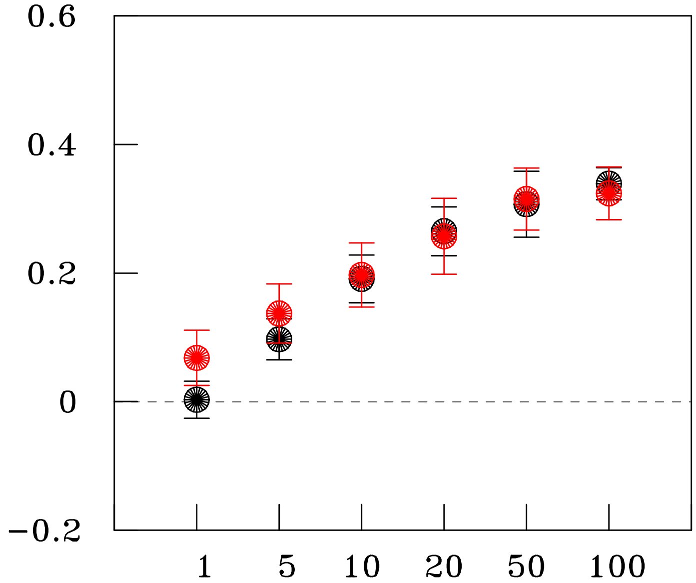


Figure 10. The degree of anisotropy, α, as a function of time averaging for the Pacific Ocean, 12^{o}N-60^{o}N. Filled circles and vertical sticks show means and standard deviations of α estimates. The horizontal axis shows the length of an interval used for temporal averaging of velocity fields, in weeks: 1, 5, 10, 20, 50, or 100 week averages. Black and red colors indicate estimates based on satellite observations and the model NPac2 run, respectively. The statistics are based on the total of 539 weeks of satellite data and 12 years of model simulation.

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